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Report on the automatic integration of solar radiation at Kew Observatory

by
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Summary

An account is given of the development and performance trials of an automatic integrating device for giving daily values of total (sun + sky) solar radiation. Circuit details are given, accuracy is assessed, and calibration technique discussed. In conclusion, future developments are outlined.

1. Introduction

Experience in the measurement of solar radiation has shown that reliable instruments and recording equipment, when repeatedly calibrated against suitable standards, may be combined to yield data having an estimated accuracy of the order of ±5% for hourly totals. Because of the very rapid fluctuations of intensity, caused by broken clouds or haze patches, it is found that errors introduced during the subsequent measurement of the charts amount to a further ±(5 - 10)%.

Of the short wave solar radiation measurements made at Kew Observatory, the most generally applicable component is that of total (sun + sky) radiation falling on a horizontal surface, and this was selected for the experiments in automatic integration to be described here.

Recording of total radiation began in 1946 (1) and had continued for three years when integrating methods were first surveyed. The solarimeters are of the Moll-Gorczynski type made by Messrs. Kipp and Zonen; their outputs are measured by Cambridge Instrument Co. thread-recorders. Measurement of the charts is done by estimating the mean intensity, hour by hour, and so summing to give daily totals. The thermopiles give a maximum D.C. output of about 10 mV on a bright summer's day. The problem was to integrate quantities of total radiation over periods of a day or less, and to be able to check the performance under all conditions.

2. The method adopted

Since the first three years' total radiation data had been analysed by estimation of mean hourly intensities with an accuracy of about 5-10%, the required accuracy of any automatic integrating device needed to be within 2-3%. Simplicity of design, stability of performance and ease of maintenance were the prime objectives if the time saved were not to be lost in attention to the equipment. The method adopted was to use a magnetic amplifier (type PDS.2 made by Electro Methods Ltd.) to drive a low inertia, permanent magnet D.C. integrating motor (type 900, 1.5 V nominal voltage, by the same firm) and a suitable counter.

/Amplifiers

Amplifiers of the type chosen have been fully described in a review article by Tweedy (2). Stability and linearity are enhanced by using two amplifier units in push-pull, and by restricting the power gain to 5000. Combined with the linear voltage-speed characteristic of the motor, the unit gives a closely linear performance with a stability of $\pm 2\frac{1}{2}\%$ for mains voltage/frequency variations of +5% and -15% (a 230V constant voltage transformer controls the supply).

Features special to the present unit include an input attenuator control to give a variable voltage amplification from 100 to 400, and a zero-setting control, which alters the effective operating point by varying a D.C. current in a separate bias winding. The result of this is to enable the output to be set at zero for zero input, or at a value close to the starting voltage of the integrating motor. The use of this control is further discussed in later sections. As shown in Fig. 1, the amplifier has been designed to match the impedance of the source.

3. History of the experiment

(i) Preliminary trials

After check calibrations had been made for linearity and suitable gain settings, the magnetic amplifier was connected to a spare solarimetric thermopile, and the motor coupled to a five-digit decade revolution counter (cyclometer type). Recording trials, started in November 1950 with a voltage amplification of 150, soon showed that the power developed at the solarimeter in winter was insufficient to enable the motor to turn the counter from say 4999.9 to 5000.0, thus giving poor correlation with the estimated totals on days of weak solar radiation.

The cyclometer was therefore replaced by a Post Office type relay counter; a suitable cam on the motor output shaft working a sensitive anemometer type of contact which in turn operated a telephone message register. The resulting performance remained satisfactory for the next year, but soon after deteriorated rapidly as the relay contacts wore out, having already far exceeded their rated life. To monitor the performance during each day, a recording voltmeter (Evershed tapping recorder) was placed in parallel with the motor across the output from the amplifier. Tests showed that this did not affect the calibration factor.

(ii) Correlation with estimated totals

Fourteen months' data (June 1951 - July 1952) were examined by plotting tabulated calories/cm^2 against the integrator counts. Superposed on this was the calibration of the integrating device as a whole, which was derived from two calculations. A plot of input voltage against counts gave the slope of the line, and the starting input voltage interpreted in terms of cal/cm^2/hr gave the intercept, as shown in Fig. 2. This question of the equivalent "starting" radiation intensity, and the method of correcting for it, is considered further in section 5(ii).

This period gave a close fit of the estimated values with the theoretical line derived from the integrator calibrations. Four calibrations were carried out during the period, and the conversion equations used were:-

July 1951	Cals = 0.034 Counts + 0.8 h *
Dec. 1951	Cals = 0.035 Counts + 2.5 h
May 1952	Cals = 0.034 Counts + 3.3 h
July 1952	Cals = 0.035 Counts + 3.4 h

These show nothing worse than a gradual increase of starting voltage under load, which was some 5mV at first and about 18mV at the end.

* See sec. 5(ii) for form of these equations.

/4.

4. Details of present apparatus

As a result of the experience outlined above, the final version of the integrating device, now in operation, was assembled in July 1952. Amplifier and integrating motor remain as before, but the relay counter has been replaced by a direct drive, dial type of counter. This is a light gear train meter, formerly incorporated in a Negretti and Zambra fan-anemometer. The torque required to start this counter is only 1/20 that required to work the relay counter.

Apart from routine stripping and cleaning of the motor every six months, the only major attention was the replacement of the gold brushes, which had become severely worn, in June 1953. This was foreshadowed by a rise in starting voltage from 12-18 mV, and erratic movement of the armature. With reasonable attention at six month intervals, the motor will start on load at 4.5 mV immediately after cleaning, and should be re-examined when this has increased to about 12 mV. These values are to be compared with the nominal starting voltage (no load), which is quoted as 4.2 mV.

5. Calibration technique

(i) Method

The impedances of the input side of the amplifier and that of the solarimeter + leads are first measured accurately with a resistance bridge. A circuit is then set up as in Fig. 3. The input voltage is fed in across a fixed resistance equal to that of the solarimeter + leads. The integrating motor and recording voltmeter remain connected to the output side as in normal running. The P.D. across both input and output terminals is measured by potentiometer during the calibration.

The zero setting control is then adjusted, as required, until the motor ceases to move backwards or forwards for zero input voltage. Its precise setting depends to some extent on the values of the input and output impedances. When no movement occurs over say 12 hours, the calibration can be done. The values of the input and output voltages give the voltage amplification factor; the former also enables the radiation not measured (through sticking) to be allowed for; the latter is a routine check on the condition of the motor. Lastly, a series of values of input voltage are plotted against integrator counts, giving the calibration factor and checking the linearity of the response.

(ii) Interpretation and application

The solarimeter, by comparison with an Ångström pyrheliometer, is found to generate a known e.m.f. for an incident radiation intensity of 1 cal/cm^2/hr. The corresponding integrator counts for this intensity can therefore be determined.

Secondly, from the value of the input starting voltage, the corresponding "starting" radiation intensity can be computed in cal/cm^2/hr. Formerly, this figure was multiplied by the length of day in hours to give the total correction for the day. This was then added to the quantity actually registered. Typical conversion equations were given in section 3(ii), e.g.:-

$$\text{Cals} = 0.035 \text{ Counts} + 0.8\ h$$

where h = length of day in hours, and the second term on the R.H.S. corresponds to the intercept in Fig. 2. This method gave good results for days of lowest radiation totals, but over-corrected the summer values. The reason for this is twofold: the full loss in the registered radiation obtains only for the fraction of the day during which the motor has actually stopped and the input is insufficient to restart it; secondly, when the motor is in motion, the value of the sliding friction is somewhat less than the static value which determines the starting voltage.

/It

It was found that the best empirically determined correction is given by adding a constant term (usually about 5-10 calories per day), which corresponds to the winter correction used above. This supports the theory that the reduced sliding friction in summer (due to the larger input signal) is compensated by the longer days. Fig. 4 contains six months' data plotted in this way against the tabulated totals.

A final point of interest lies in the shape of the integrator calibration curve near the zero. Recent experience has shown that this becomes slightly non-linear at high gain settings, and it becomes necessary to decide what is the form of the conversion equation giving the best fit under all conditions. Fig. 5 shows that a straight line can be drawn which is close to the experimental points at all places. This intercepts the axis at the effective starting voltage (less than the measured value in practice). This intercept determines the correction term to be used. The zero setting control can be used to shift the operating zero close to this effective starting voltage, thus reducing the correction term to a minimum. On the other hand, it is inadvisable to do this if the effective and measured starting voltages are nearly coincident, in case the motor moves slightly during periods of zero input.

6. Assessment of present performance

It must be remembered that the tabulated totals have to some extent been used as the reference for comparison in this experiment. This approach is justified as far as errors of estimation (introduced in the process of tabulation) are concerned, since these are found to be nearly randomly distributed about the true values*. Thus, provided a minimum of six months' data is used at one time (as in Fig. 4), with a check calibration of the integrator done at the beginning and end of each period, a valid comparison can be made.

In addition to the long term comparison, it has also been possible to carry out spot checks in the following way. A series of clear days is chosen, and the daily totals of solar radiation are found by planimetering the charts of the recording voltmeter (in parallel with the integrating motor). The totals are compared with the integrator counts for the same days, and hence the calibration of the voltmeter is effected (in terms of integrator counts). The calibration is then repeated (in terms of cal/cm^2/hr) by alternately shading and unshading the solarimeter; the difference in deflection between the two readings on the voltmeter record is then equivalent to I sin θ , where I is the intensity given by the Ångström pyrheliometer and θ is the sun's elevation at the time.

One further piece of evidence, though somewhat indirect, arose during the development of a bimetallic actinometer (3) which is also designed to give daily values of total (sun + sky) radiation. Its performance was originally checked with reference to the estimated totals since the integrating device was still in the experimental stage (June - November 1951). Even at this stage, however, a much improved correlation was obtained when the automatically integrated values were used as reference.

Finally, some comments on the scatter shown in Fig. 4 are perhaps called for, since this is largely attributed to errors other than those produced by the integrating device. The first point concerns the use of one solarimeter with a thread-recorder for the standard of reference, and a second solarimeter with the integrating device under test. Part of an investigation into errors inherent in radiation data (see Footnote) compared independent tabulations of the same daylight illumination records, which correspond closely in appearance with total radiation records (4). Also considered were tabulations of the records of the two solarimeters used here, when both were used in conjunction with thread-recorders. The correlations of the two sets of data were practically the same ($\sigma \sim 6\%$) and hence, in this respect, the use of a different solarimeter with the integrating device is justified.

* these results, based on trials in which many charts were measured independently by different observers, are due to Mr. R.H. Eldridge.

/The

The scatter of individual days is therefore attributed to errors caused by the minute by minute sampling of the thread recorder, the effect of its lag constant, and the random errors of tabulating ($\sigma \sim 2\%$ for daily totals). In conclusion, the estimated accuracy of the present apparatus is considered to be of the order of 2 - 3%.

7. Future developments

This report is presented at this stage of the work because the principle and accuracy of the method have been found satisfactory. Furthermore, the existing equipment requires no further modification for the stated purpose: namely, the integration of solar radiation over periods of a day. Certain extensions of the method, however, are contemplated.

The present amplifier has a continuously variable gain-setting knob. A future version would more conveniently have three or four settings for use at different times of the year. Finally, a time-marking system will be utilised to operate an automatic camera to photograph the counter-dial in order to give hourly totals of solar radiation.

8. Acknowledgments

I wish to acknowledge the help and guidance, during the preparation of this report, of Dr. G.D. Robinson, who planned the experiment from its inception in 1949. Thanks are also due to Mr. A.J. Lander for carrying out subsequent modifications to the original apparatus.

9. References

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2. Tweedy, S.E. Electronic Eng., 20th Feb. 1948

3. Blackwell, M.J. M.R.P. 791, 1953

4. Blackwell, M.J. M.R.P. 831, 1953

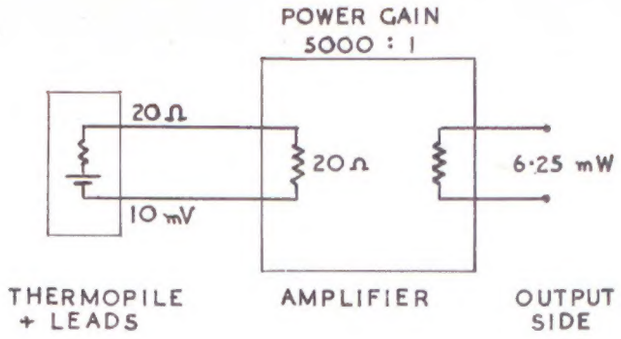

FIG:1 — CIRCUIT

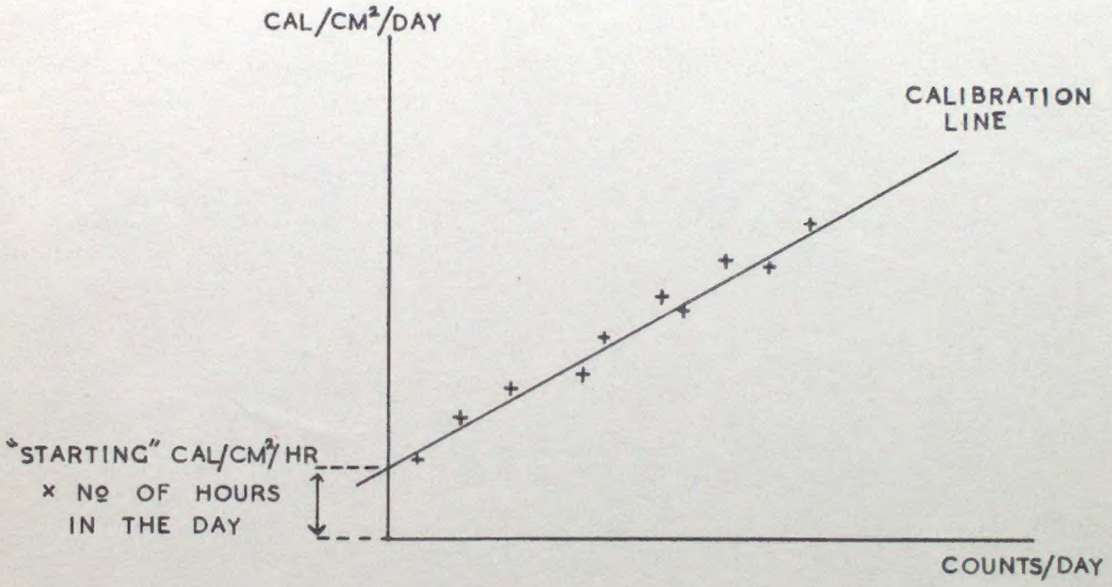

FIG. 2 — PRESENTATION OF DATA

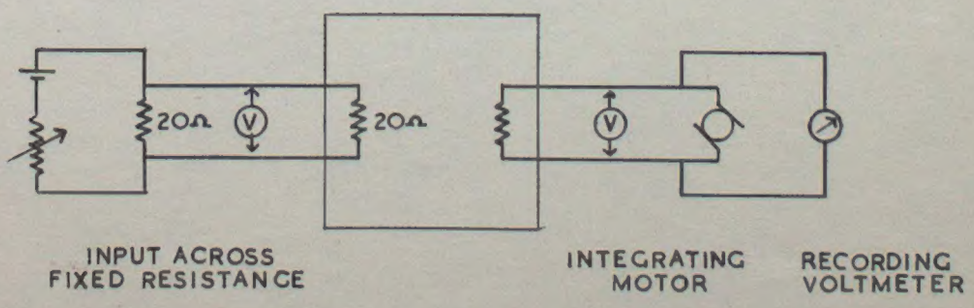

FIG.3 — CALIBRATION CIRCUIT

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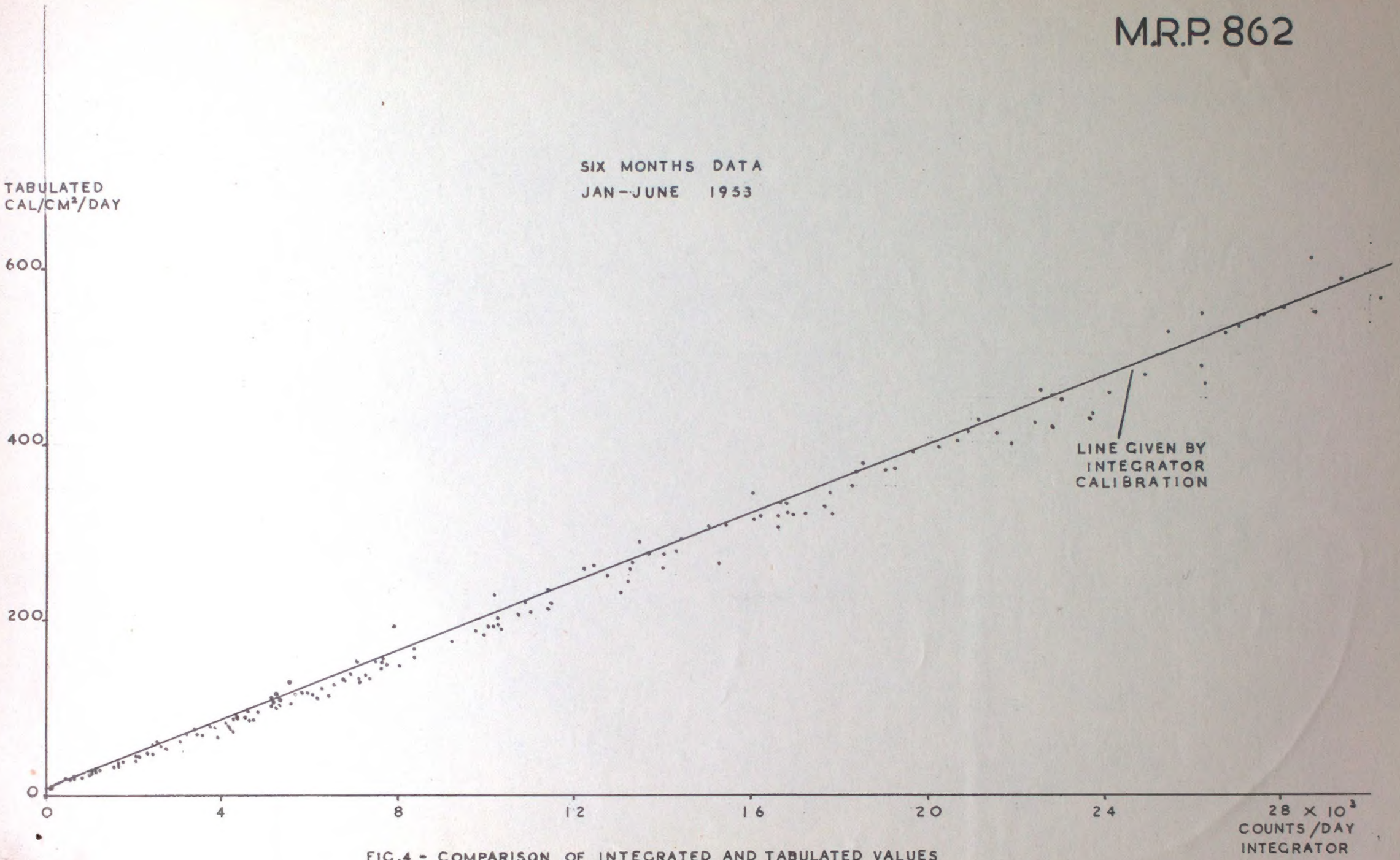

FIG.4 - COMPARISON OF INTEGRATED AND TABULATED VALUES

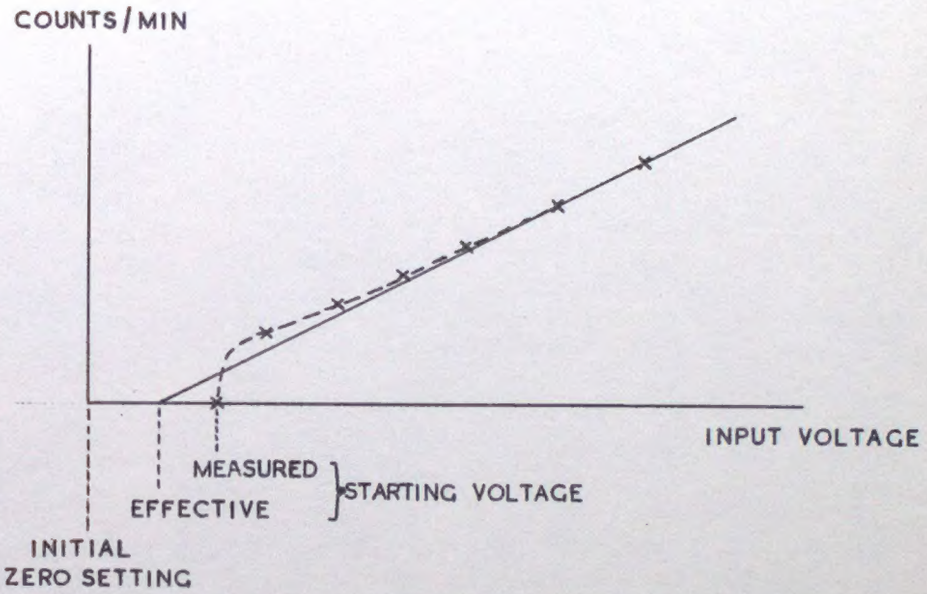

FIG . 5 — EFFECTIVE STARTING VOLTAGE